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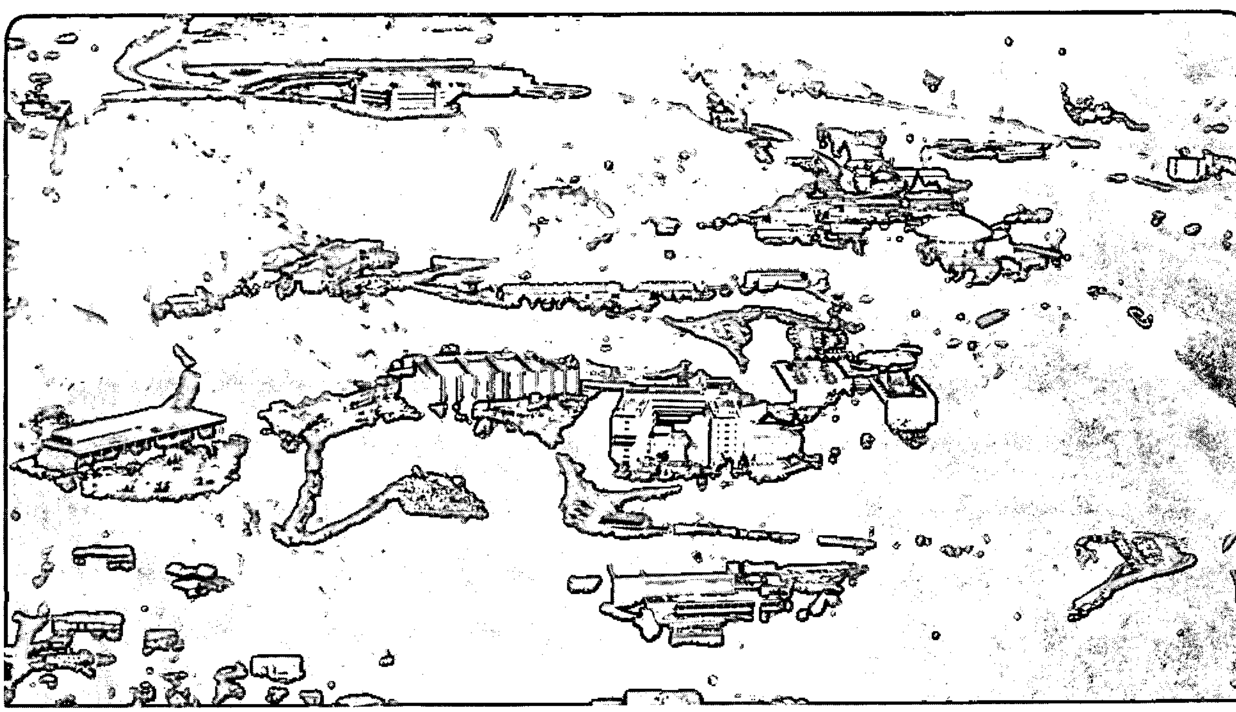

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ASTROMAG is a particle astrophysics experiment which will operate in space for a period of two years or more. Momentum and charge resolution of cosmic rays is achieved using particle detectors in a magnetic field. In the ASTROMAG experiment, this magnetic field is provided by a pair of superconducting solenoids. The ASTROMAG superconducting magnet is supposed to have a zero net magnetic dipole moment so that magnetic torques introduced to the space craft are kept at a low level. Dipole moment correction coils, which can provide up to 11,000 Am^2 of correction in the Z direction and 7,000 Am^2 of correction in the X and Y directions, appear to be practical using superconducting correction coils which are mounted on the superfluid helium tank in a region 0.5 meters wide halfway between the main ASTROMAG coils. The superconducting dipole moment correction coils should be capable of reducing the ASTROMAG magnet net dipole moment to 100 Am^{-2} or lower.

BACKGROUND

The ASTROMAG superconducting magnet is designed so that the magnet produces zero net magnetic dipole moment. The coils for the free-flyer ASTROMAG each have 2924 turns carrying 800 amperes, and the average coil radius is 0.69 meters[1,2]. The two coils are supposed to be identical with the same average radius and turns number. The two solenoid coils share a common axis and they are spaced 1.67 meters apart so that the solenoid average current planes are parallel and separated by a distance of 1.89 meters. The two coils are powered in series at opposite polarity so that the net dipole moment is zero.

The nominal design condition given in the free-flyer ASTROMAG report is that the net dipole moment in any direction (along the axis or perpendicular to the axis) is no more than 100 Am^2 (about 0.0025 percent of the magnetic moment of a single coil powered to full current). There are three sources of error which result in noncancellation of the dipole moment. They are: 1) the number of turns in the two coils is different; 2) The average current radius in the two coils is different, and 3) the current plane of one solenoidal coil is tilted with respect to the current plane of the other coil. The first two will yield a dipole moment with an axis parallel to the primary solenoid axis. The third will yield a magnetic moment with an axis perpendicular to the primary solenoid axis.

A single coil will generate a magnetic moment of about 3.504×10^6 Am^2. The net magnet dipole moment from the magnet will interact with the earth's magnetic field to generate a torque which can adversely affect the attitude of the space craft. In orbit, when the earth's magnetic field of 0.3 gauss is perpendicular to the axis of the solenoid, the worst case torque generated by a single coil carrying 2.342×10^6 amperes will be 105 Nm. Without correction coil, the ASTROMAG magnet might produce torques as high as 0.2 Nm, which is too high for the free-flying spacecraft.

In order to insure that the net dipole moment be low enough so that ASTROMAG can be operated on a free flyer, an orthogonal set of active superconducting correction windings mounted on the superfluid helium tank has been proposed. These correction coils should be capable of developing dipole moments up to about 10000 Am^{-2} in the three orthogonal directions. These coils would operate in the persistent mode at relatively low current (of the order of 15 amperes) so that the leads to these coils do not have to be gas cooled and so that they do not contribute significantly to the boil-off from the superfluid helium cryogenic system.

THE LOCATION AND DESIGN OF THE SUPERCONDUCTING MAGNETIC DIPOLE MOMENT CORRECTION COILS

It is clear that the superconducting dipole moment correction coils must be located somewhere on the superfluid helium tank. The magnetic dipole moment coil must be located symmetrically about the geometric center of the magnet in order to prevent coupling between the correction coils and the main ASTROMAG magnet coils. The main magnet coil persistent switch, the cryostat valves and the gas cooled leads are located on the surface of the tank at the lowest field region on the tank surface (about 0.5 T in the radial direction). The magnetic dipole moment correction coils should be located on the superfluid helium tank in the same general region. The arguments in favor of this location are as follows: 1) This region is a low field region; there is a greater current margin in the superconductor which is in the correction. 2) Since the magnetic moment correction coil location is a low field region, the magnetic forces on the correction coils can be reduced. 3) The correction coils and their persistent switches are located close to the service ports for the ASTROMAG cryostat. 4) The magnetic field generated by the magnetic dipole moment correction coils will have little effect on the physics detectors. 5) The effect of correction coil placement errors on the mutual inductance between the main coil circuit and the correction coil circuit is minimized.

Let us assume that the required correction of magnetic dipole moment along the axis of the solenoid is just over 0.3 percent of magnetic moment of a single coil, and that the required correction perpendicular to the axis of the solenoid is 0.2 percent of the magnetic moment of a single coil. For ASTROMAG, the Z moment correction is 11000 Am^2 and the R moment correction is 7000 Am^2. Figure 1 shows the proposed design for a three axis dipole moment correction system mounted on the outside of the helium tank. Shown in Fig. 1 are two Z magnet moment correctors which are solenoid coils 1.45 meters in diameter and 0.50 meters apart. The R correction coils shown in Fig. 1 are two pairs of solenoid coils (one pair for the X direction and one pair for the Y direction). These coils are 0.46 meters in diameter and they are mounted 1.44 meters apart. These coils can be connected to the tank directly because their stored energy at full current is less than 1 kJ.

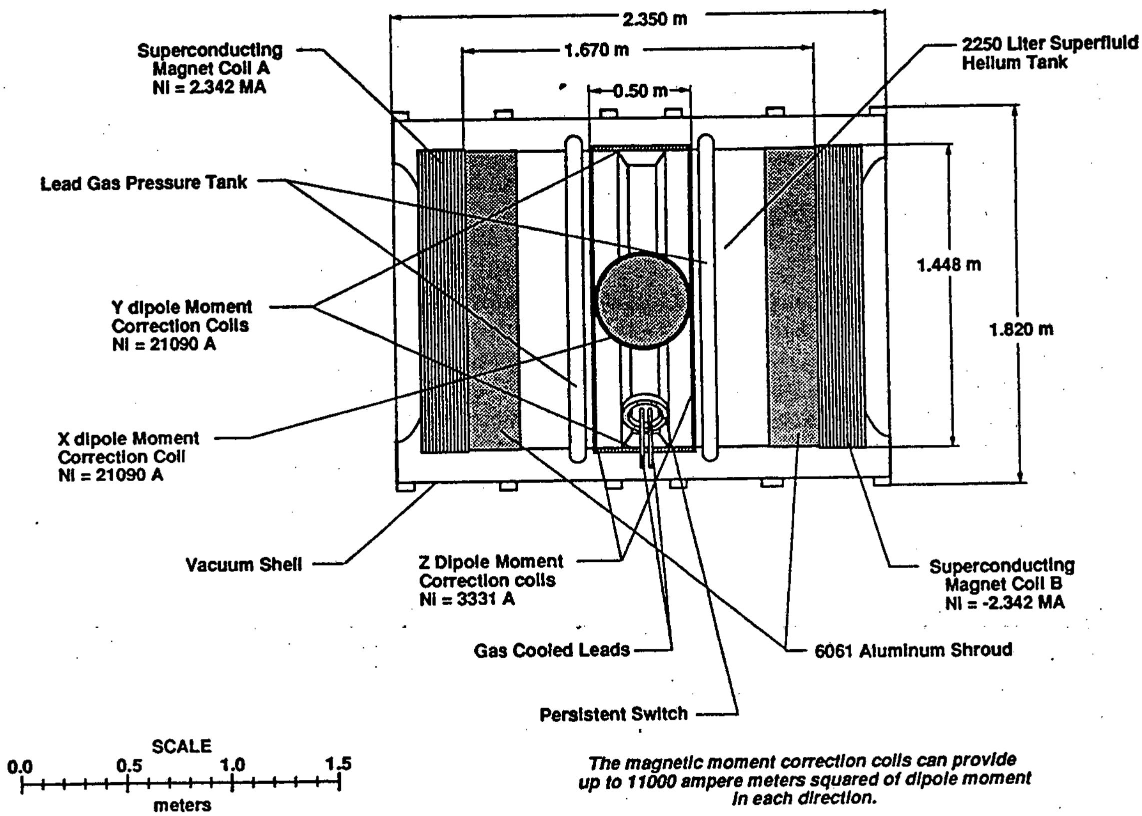

Figure 1 The Location of the Magnetic Dipole Moment Correction Coils on the Superfluid Helium Tank of the Free-flyer ASTROMAG Magnet Cryostat

Table 1 The Basic Parameter of the Magnetic Moment Correction Coils for a Free-flyer Version of ASTROMAG Magnet

Parameter	Z Moment Correction Coils	X - Y Moment Correction Coils
Number of Coils per Circuit	2	2
Number of Turns per Coil	240	1600
Coil Inner Radius (mm)	1447	225
Coil Outer Radius (mm)	1453	235
Coil Length (mm)	10	24
Circuit Design Current (A)	13.9	13.2
Coil Dipole Moment (Am^2)*	5500	3500
Circuit Self Inductance (H)	0.639	5.05
Circuit Stored Energy (J)*	61.7	440
Peak Induction in Coil (T)*	~0.7	~1.0
Superconductor T_c (K)*	~7.4	~7.1

* At the Design Current

For the correction coils, the projected area is πR^2 where R is the central radius for the current. For the Z magnetic dipole moment correction coils shown in Fig. 1, R = 0.725 m. Thus, the Z coil projected area is 1.651 m^2. When the two coils are hooked together in series, they are expected to generate a maximum dipole moment of 11000 Am^2. The design ampere turns required for each coil is about 3331. The design calls for 240 turns of insulated 0.3 mm diameter single core superconductor with a copper to superconductor ratio of 3. (The uninsulated diameter of the superconductor is 0.22 mm.) The maximum coil design current for the Z dipole moment correction coils is about 13.9 amperes. A single core superconductor can be made to form a joint with no resistance (in the low field region of the ASTROMAG magnet). Thus, the decay time constant for the correction coil circuit can be made to be much longer than the decay time constant for the ASTROMAG main coils. For the X and Y magnetic dipole moment correction coils, which are shown in Fig. 1, R = 0.23 m. Thus, the X and Y correction coil projected area is 0.1662 m^2. The two coil set, when the two coils are hooked together in series, is expected to generate a maximum dipole moment of 7000 Am^2. The design ampere turns required for each coil is about 21090. The X and Y coil design calls for 1600 turns of the same superconductor as the Z magnetic moment correction coils. The design maximum current for the X and Y dipole moment correction coils is about 13.2 amperes. At 2 K and 1.2 T, the superconductor critical current should be greater than 60 amperes (for a superconductor with a critical current density of 2000 A mm^{-2} at 4.2 K and 5.0 T).

CORRECTION COIL COUPLING, SWITCHES AND OTHER ISSUES

The mutual inductance between the main coil circuit and the three orthogonal dipole moment correction circuits is nominally zero. The three dipole moment correction circuits are nominally not coupled to each other either. Errors in the placement of the dipole moment correction coils, with respect to each other and the main magnet coils, will result in a small amount of mutual inductance between the main coil circuit and correction coil circuits. (It is important that all of the coils be symmetric about the magnet center in each of their axis directions.) If the placement errors are below 0.2 millimeters, there is no adjustment of the correction coil current needed during the coil charging phase except as needed to adjust for the net magnetic moment generated by the main coils.

While the mutual inductance of the three orthogonal correction coil circuits with the main coil circuit is nominally zero, individual correction coils are coupled to the main coil circuit. The coupling between the individual coils and the main coil circuit can cause voltages to be developed with respect to ground in the correction coils when the main magnet coils quench. The maximum rate of current change in the ASTROMAG magnet during a quench is about 720 A s^{-1}. The mutual inductance for a single Z dipole moment correction coil to the main coil circuit is 285 mH; the voltage to ground in this coil will be just over 200 volts. The mutual inductance for a single X or Y dipole moment correction coil is 155 mH; the voltage to ground in these coils will be just over 110 V. Neither of these voltages to ground is excessive.

Since the maximum stored energy for the correction coils is less than 500 joules, the switch can be designed to absorb the entire energy of a circuit quench. The mass of the switch for the X and Y correction circuits need only be greater than 10 grams. It is difficult to visualize a switch mass which is less than 100 grams. The open circuit resistance of the switch can be as little as 1 ohm. The closed circuit resistance of the switch must be zero. The switch and correction magnet circuit should be made with single core superconducting wire. Each of the dipole moment correction coils will be hooked in series with its corresponding opposite member. As a result, three pairs of leads have to be brought out of the 1.8 K region. These leads should be capable of carrying the full correction coil current for 100 seconds. Using copper nickel leads, the heat leak into the 1.8K region can be reduced to about 2 mW for the six leads. If these leads are cooled by helium gas venting from the tank as they go out to the first shield, the heat leak into the tank can be reduced to well below 1 mW. Charging the three sets of correction coils from zero to full current in 100 seconds will deposit around 100 joules of energy into the leads if their total length from the 1.8 K region to 300 K is 2 meters.

The primary magnetic forces generated by the dipole moment correction coils are generated by the reaction of the current in the dipole moment correction coils with the magnetic field generated by the main ASTROMAG coils. This force will generate a net force on the helium tank and hoop forces in the dipole moment correction coils. In the region of the Z dipole moment correction coils, the magnetic field is predominantly radial. This radial component is about 0.5 tesla. This radial component will generate a force along the axis of the magnet. At full current, (about 13.9 amps), the Z force generated by each of these coils is approximately 7590 N (0.774 metric tons). Both correction coils will produce a force in the same direction. The forces, due to the longitudinal field component, will produce a hoop force in the correction coils. At the point where the Z correction coil is located, the longitudinal component of field is 0.29 T. A correction coil with a cross-section area of 1.2 cm^2 will have a hoop stress of about 6 MPa. If the attachment point of Z dipole moment correction coil is part of the helium tank , these magnetic forces should not be a problem. The magnetic forces on the X and Y dipole correction coils are somewhat more complicated. The X and Y correction coils are assumed to be flat circular windings. The component of the field perpendicular to the plane of the coil will produce a net hoop force in the coil. If the coils have a cross-sectional area of 3.6 cm^2, and field component perpendicular to the coil plane is 0.45 T, the average hoop stress will be about 6 MPa. The force perpendicular to the plane of the coil is more complex to calculate because the flux component in the radial direction of the X or Y correction coil varies as one goes around the X or Y correction coil. On average, this radial flux component is about 0.061 T. At full current, (about 13.2 amps), the force generated by each of these coils is approximately 1850 N (0.189 metric tons). The force direction will be in the direction of the axis of the correction coil. (X correction coils will produce X forces; Y correction coils will produce Y forces.) Both correction coils will produce a force in the same direction. The connection between the X and Y correction coils and the helium tank will occur near the points where much of the X and Y forces are generated within the correction coils.

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